

# Development of a Multi-Stage Filter System for Cabin Ventilation Systems on the ISS and Future Deep Space Missions

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The National Aeronautics and Space Administration's (NASA's) deep space exploration missions will be of significant duration requiring long-life and reliably performing spacecraft cabin ventilation filters. A particulate filter system is being developed at NASA Glenn Research Center (GRC) to meet the challenges of these remote and long duration missions. The capabilities and features of the filter system are expected to expand the life and reduce the maintenance requirements over that of the current ISS filter by providing pre-filtration stages with novel regenerable techniques. The filter system is also designed to be compatible with the interfaces and performance requirements of the ISS distributed ventilation architecture in the US modules to facilitate testing on ISS type test or mock up platforms. Currently, a prototype of the filter system is undergoing tests in a custom configured filter test stand at the NASA GRC. The test stand provides the same range of flow rates produced on the International Space Station (ISS) distributed architecture, and is equipped and instrumented to perform filter tests based on industrial test standards. The test stand has been used successfully to perform filter and flow performance test on returned ISS Bacterial Filter Elements. Similar test protocols were used to characterize the performance of the current filter system. The filter system was tested with different performing grades of filter media and different particle standards that simulate the range of particulate matter particles and debris the filter will see during a mission. This paper will present results and analysis of the test data to guide and provide input to the next generation filter system.

## Nomenclature

ESM	=	Equivalent System Mass
$E_T$	=	filter overall efficiency
$N$	=	Particle counts
$P$	=	filter particle penetration
PAO	=	Polyalphaolefin
$Q$	=	flow rate
$\kappa$	=	permeability
$\mu$	=	viscosity

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## I. Introduction

AS NASA plans for space missions beyond Low Earth Orbit (LEO), the air revitalization needs and requirements in a spacecraft life support system will need to be revised for increased life and lower maintenance. The removal of particulate matter (PM) is of utmost importance for human spaceflight to minimize the risk of detrimental effects of suspended particulates to both the crew and on-board equipment. State-of-the-art (SOA) air filtration systems, which primarily employ filter media-based components, such as High Efficiency Particulate Air (HEPA) media-based filters, are a very mature and reliable technology, and are extremely effective in removing PM of all size ranges from the cabin atmosphere of a spacecraft. However, these filters are life limiting and require both replacement and regular maintenance that contributes to both launch up-mass and crew time for our present LEO manned platform, the International Space Station (ISS). The intrusion of planetary dust during surface missions will compound the PM matter load on the filter over the duration of the mission. The portion of dust collected on EVA suits and equipment that is not contained or removed at the airlock prior to entry into the pressurized cabin will likely be considerable and will have to be removed by the air filtration system in addition to the internally generated PM.<sup>1</sup> In this paper, we discuss the design and testing of an alternative to passive single-used media filter systems used in the ISS and other spacecraft systems, which have the potential to reduce additional launch or resupply mass, and eliminate crew maintenance.

## II. ISS Filters

For particulate matter removal, the ISS utilizes a distributed filtration architecture with media-based filters known as Bacteria Filter Elements (BFEs) installed in the inlets of various air ducts in this architecture. These ISS BFEs, one shown in Fig. 1, contain pleated borosilicate HEPA media in a rectangular aluminum frame with outside dimensions of 73.7 cm  $\times$  10.2 cm  $\times$  11.1 cm. The HEPA media is covered with a 20-mesh Nomex<sup>®</sup> screen on the inlet side of the filter and an aluminum coarse screen on the outlet side.

The 15+ years of operational experience on ISS with these state-of-the-art HEPA media filters has provided useful data on replacement intervals and crew time for maintenance. The replacement for these BFEs have recently been reassessed<sup>2</sup> and are now recommended to be replaced on a 2.5 to 5 year cycle based on location in the ISS. Additionally from operational experience, it has been observed that the BFE inlets accumulated large amounts of fibrous PM debris (primarily cloth fibers, skin flakes) due to the lack of sedimentation in a microgravity environment. Based on experience, the crew performs vacuuming of these inlets on a weekly basis as part of their housekeeping activities.

NASA's Advanced Exploration Systems (AES) project has supported the development of new environmental control and life support systems (ECLSS), including air filter systems, which can demonstrate advanced capabilities for missions beyond low-Earth orbit (LEO). A recent Mars related trade study<sup>2</sup> of filter systems quantified the substantial launch mass savings and lower maintenance time costs that would be realized for a filter system that offers regeneration or reduced-maintenance technologies.



**Figure 1: ISS Bacteria Filter Element (BFE) with Nomex<sup>®</sup> inlet screen removed.**

### III. Bacterial Filter Element Scroll Filter System

The design of the present filter system is fashioned after the Scroll Filter System (SFS) which has been previously reported (see Refs. 3 and 4). The present prototype shown in Fig. 2 integrates the three filter stages of the SFS, typically individual modules of the SFS, into a single unit. The three filter stages are briefly described as:

1. Screen Roll Filter (SRF) – A screen filter with additional screen material which is provided by a supply roll on a motorized spooling mechanism. When the screen material is loaded with PM it can be changed by advancing the roll until a new section of the screen material is exposed in the flow.
2. Regenerable Impactor filter - a pre-filter which uses inertial impaction through area reducing devices (e.g. orifice or slits) for separating and collecting particles several microns and larger on regenerable collection bands placed just downstream of the reducing area devices.
3. Scroll Media Filter (SMF) - A pre-filter or intermediate stage filter that provides multiple changes of the filter media through a motorized scrolling or indexing mechanism. The filter media can be arranged in a pleated pattern, using support spindles, to increase the filtration surface area.

A finishing high efficiency filter can be added as the last filtration stage. For further details on the SFS, the reader is referred to Refs. 3 and 4. The frame of the present filter system was designed to be compatible with the ISS BFEs. The footprint of the filter frame was designed to fit directly inside and interface with the housing for the BFEs. The present prototype will be referred to as the Scroll BFE in this paper.

### IV. Test Methods and Materials

In order to advance the maturity of the BFE Scroll filter system, its performance had to be tested under relevant and standard test conditions. So testing was performed on an upright test stand, shown in Fig. 3, which was originally designed and used for leak testing of the ISS filters; the details of this test setup were discussed in earlier work.<sup>5-7</sup> Figure 3 shows a photo of the present test stand including several changes to accommodate the capability to use a solid particulate challenge in addition to the liquid aerosol challenge (a capability utilized in our previous work). A flow diagram to the right of the photo more clearly shows the flow paths, the connections, and the links for the equipment and instruments used.

The flow expands through the lower expanding duct section to accommodate the narrow cross-section of the Scroll BFE filter test article (positioned in the middle of the duct); the challenge aerosol is introduced near the bottom of this duct section to allow for mixing prior to reaching the inlet of the test article. A contraction duct section collects the airflow exiting the filter and directs it to a 7.6 cm diameter exit tube. The downstream samples are measured from a port ~6 tube diameters downstream of the entrance to this exit tube to ensure that airflow will be fully mixed. The filter system was tested at several flow rates below and at the nominal ISS BFE flow rate of 1.98 m<sup>3</sup>/min.

Two different aerosol challenge test methods were performed on the different media in this study. Each method followed, or was guided by, a different industrial test standard. In the first, a liquid aerosol was used as the challenge following IEST-RP-CC034 and MIL-STD-282<sup>8,9</sup> industrial test standards. An ATI aerosol generator (model TDA 4B) along with a specially designed ATI impactor generated the challenge aerosol. A TEC Services photometer (model PH-4) was used to perform the penetration measurements. The aerosol generator produces a particle size distribution with a mass mean aerosol diameter of 0.303 microns which meets the standard for the Most Penetrating Particle Size (MPPS) for high efficiency filters. The aerosol generator used Polyalphaolefin (PAO) as the aerosol solution. The photometer was calibrated for the PAO aerosol and was plumbed to sample at points upstream and downstream of the filter (as shown in Fig. 3); the instrument's output measurement is in percentage penetration of the upstream aerosol concentration.

A solid dust challenge was also performed on some of the media to cover a larger range of particles sizes than in the liquid aerosol challenge, from submicron to larger than 100  $\mu\text{m}$ . This testing technique is typically used on Heating, Ventilation, and Air Conditioning (HVAC) grade media which are lower performing media that allow larger size particles to pass through. Several modifications were made to reconfigure the test duct to follow general HVAC filter testing standards.<sup>10,11</sup> A TOPAS-GMBH solid aerosol generator using International Organization for Standards (ISO) 12103-1, A2 Fine Test Dust (FTD) pneumatically injected the solid dust challenge in the flow near the bottom of the expanding duct section. Table 1 shows the distribution of particle sizes of the ISO FTD, which partially contains small cotton fibers that more realistically represent indoor, or spacecraft cabin<sup>12</sup>, generated particulate matter. Particle sizes from < 1  $\mu\text{m}$  to 176  $\mu\text{m}$  are present in the simulant. Two Optical particle counters, one upstream and one downstream of the filter, were used for counting and sizing particles to calculate particle penetration and collection efficiency.



(a)



(b)

**Figure 2: Scroll BFE filter – (a) inlet face showing the screen, (b) outlet face showing pleats**

**Table 1: ISO Fine Test Dust particle size distribution**

ISO 12103-1 ARIZONA TEST DUST CONTAMINANTS A2 FINE GRADES	
Iso Test Dust Particle Size Distributions by Volume %	
<i>Size Micrometer</i>	<i>ISO 12103-1, A2 Fine Test Dust % Less Than</i>
0.97	4.5 – 5.5
1.38	8.0 – 9.5
2.75	21.3 – 23.3
5.50	39.5 – 42.5
11.00	57.0 – 59.5
22.00	73.5 – 76.0
44.00	89.5 – 91.5
88.00	97.9 – 98.9
124.50	99.0 – 100.0
176.00	100.0

(Source: <http://www.powdertechinc.com/product/iso-12103-1-a2-fine-test-dust/>)

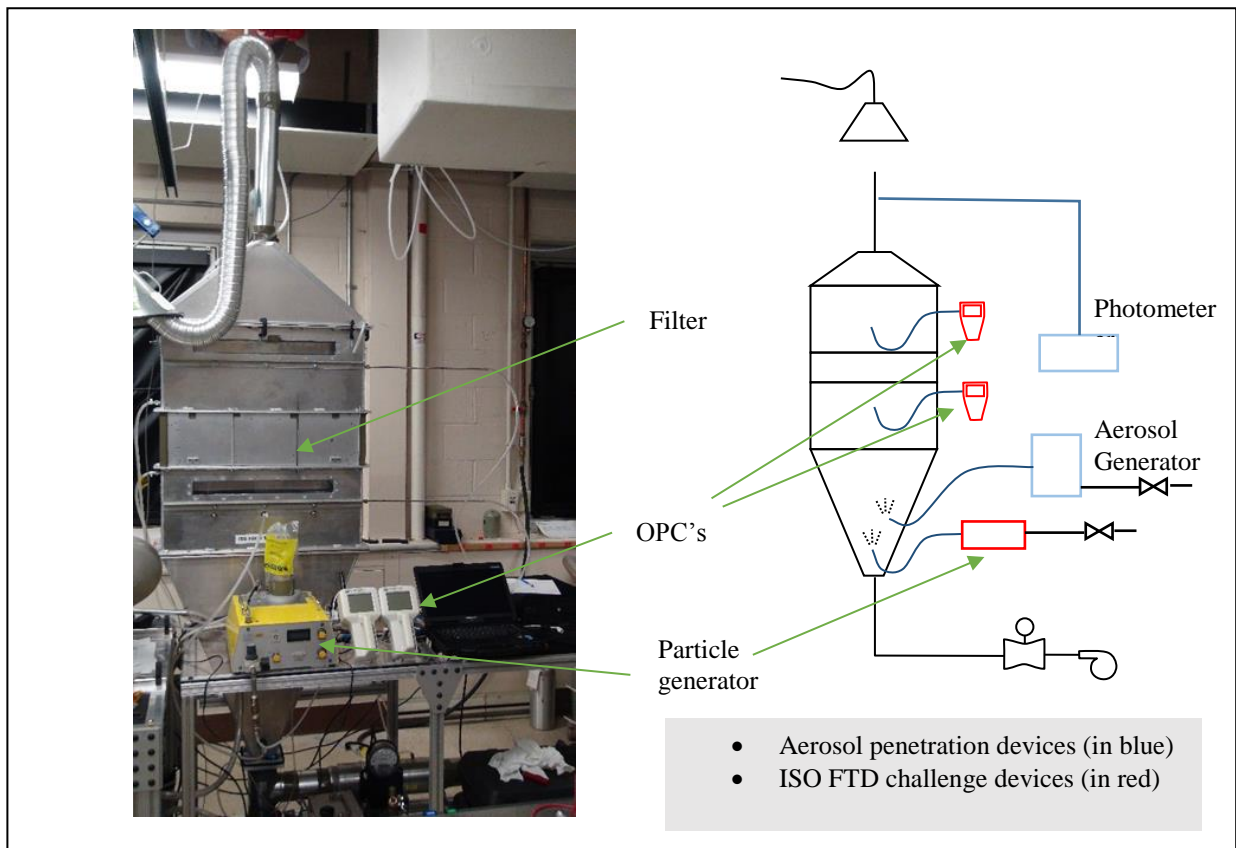
In addition, an elbow in the test duct between the Venturi flow meter and taped duct section was modified to allow removal of any sedimented particulates. After these modifications were made, the velocity profile in the duct was measured over the test article cross-section and was found to provide about 13% flow uniformity over 64% of the duct midspan at a flow rate of 1.98 m<sup>3</sup>/min. Tests were performed under ambient temperature and pressure conditions. Conditions were typically 21-24°C and 97-99 kPa during pressure drop and penetration testing.

Since the different stages of the BFE Scroll filter individually provide specific filtration functions, the approach was taken to test specific components on their own and in combination. In the present work, the filter was tested under fully and partially staged configurations:

1. Partial configuration: SRF and Impactor filter (no media in the SMF stage).
2. Full configuration: SRF, Impactor filter, and SMF stages using different grades of filter media.
3. Reference test: Flat sheet of filter media only.

Different grades of media were chosen to test the range of performance of the filter. Table 2 lists the different grades of media tested. First, a commercially available filter fabric made of polyester felt material with a rating of 5  $\mu\text{m}$  was chosen as the pre-filter media (no manufacturer's pressure drop data available). Although this media, which will be referred to as the felt media, is typically used in liquid filtration, its thickness and permeability seem suitable for its use as a pre-filter in the Scroll BFE. The thickness of the media, while substantially thinner than commercially available air pre-filter media which are typically 12 mm and thicker, is still somewhat thicker than the alternative high efficiency media which is typically < 1 mm. Media thickness as a design parameter is important because it affects the size of the roll of media that can be accommodated in the SMF assembly. Furthermore, the scrolling of the media over the rollers and inside the guide tracks becomes more difficult with increasing thickness of media. The felt media's availability in 1.8 mm thick sheets and rolls at the 5  $\mu\text{m}$  rating allowed it to be easily integrated into the SMF stage.

Secondly, a sample of a high efficiency media filter with a collection efficiency of 60% for submicron particles was obtained from Hollingsworth and Vose (H&V), a filter media manufacturer. The media will be referred to as the high efficiency (HE) media. The manufacturer's product data sheet reports an average value of pressure drop of 44.8 Pa @ 5 cm/s media velocity for this filter class (with some variation among lots). This specification provided a good baseline from which to compare its performance in the present filter system. The purpose of including the high efficiency media in this study was to test the performance and operation of the Scroll BFE at the high filtration efficiency range. Lastly, a high efficiency electrostatically charged media (referred to as HE electrostatic media) was also obtained from H&V. This media is very attractive for this application because it offers high collection efficiency at very low pressure drops, and the media is thin and lightweight.



**Figure 3: Picture and diagram of filter test stand**

**Table 2: List of filter media used in testing**

Media	Nominal pressure drop (at 5 cm/s) [Pa]	Efficiency (%) at 0.3 $\mu$ or filtration rating
Polyester felt		5 $\mu$ m
HE	44.8	60%
HE electrostatic	3	89%

## V. Mass analysis

In the process of developing the Scroll BFE and fabricating a working prototype with many of the components that would be similar in a flight design, a medium fidelity test article was developed. The opportunity to test the current prototype provided a preliminary design point to revise estimates for mass, volume, and power for future trade studies on centralized and distributed air revitalization architectures as was discussed earlier in this paper.<sup>13</sup>

Table 3 shows a breakdown of the masses of the BFE scroll filter test article, with a corresponding estimate of potential mass savings if the design was to proceed to a flight unit.

**Table 3: Mass breakdown of BFE scroll filter test article, along with mass estimates for a similar design flight unit.**

BFE scroll filter	Present Design Mass (kg)	Flight Design Mass Estimate (kg)	Mass Savings (kg)
Housing	4.13	2.96	1.17 (28%)
Screen stage	0.45	0.25	0.20 (44%)
Impactor stage	1.06	0.72	0.34 (32%)
Media filter stage	1.81	1.61	0.20 (11%)
Total Mass	7.45	5.54	1.91 (26%)

The present BFE scroll prototype filter design has a calculated mass of 7.45 kg, and when weighed in the lab had an actual mass of 7.35 kg. The likely discrepancy is in the weight of various 3D printed parts for which the volume is known accurately from the drawings and 3D models, but the density of the as-printed parts are not.

The mass analysis identified and quantified mass savings that could be implemented in a flight design using similarly designed internals. As shown in Table 3, a mass reduction of 26% was achieved resulting in a 5.44 kg mass estimate for a flight unit. The mass reductions identified could be mainly achieved with reduction in thicknesses and machining of various non-load bearing structural components. These reductions were typical of those incorporated in flight articles and based on engineering judgement; for a flight article, this type of mass reduction would need to be verified by structural loading analyses including an assessment of launch loads. The volume of the Scroll BFE was supposed to match the volume of the ISS BFE's but ended up being slightly taller to accommodate the mechanical components employed for scrolling of the filter media and screen material and the regeneration of the impactor filter.

## VI. Results

### A. Benchtop tests

Before the Scroll BFE was tested in the flow apparatus, its regeneration and self-replacing media operations were verified on a benchtop setup. Partial disassembly of the filter system was required to observe the scrolling mechanism. During these tests, the HE and the HE electrostatic media were observed to move smoothly through the full extent of pleat tracks, and the tension was maintained throughout the media as well as during and at the end of the scrolling operation. The same was observed for the screen material in the SRF and for the bands on the Impactor filter, which were found to rotate smoothly along the scrapper blade used to remove collected PM debris.



When the felt media was tested, it was observed that the increased thickness of the media caused it to snag and pull away from the tracks during the scrolling process. The resulting added friction and tension led to considerable stretching of the media that reduced the width of the media—thus increasing the chances of leaks. These issues were mitigated by fabricating new track plate assemblies through 3D printing. They provided thicker slots and chamfering of the track entry to ensure better insertion and guiding of the media edges into the tracks. Roller bearings were also added to the spindle ends of the rollers which further facilitated the folding of the media pleats because of the reduced rolling friction and easing of excessive tension on the media.

## B. Performance curves

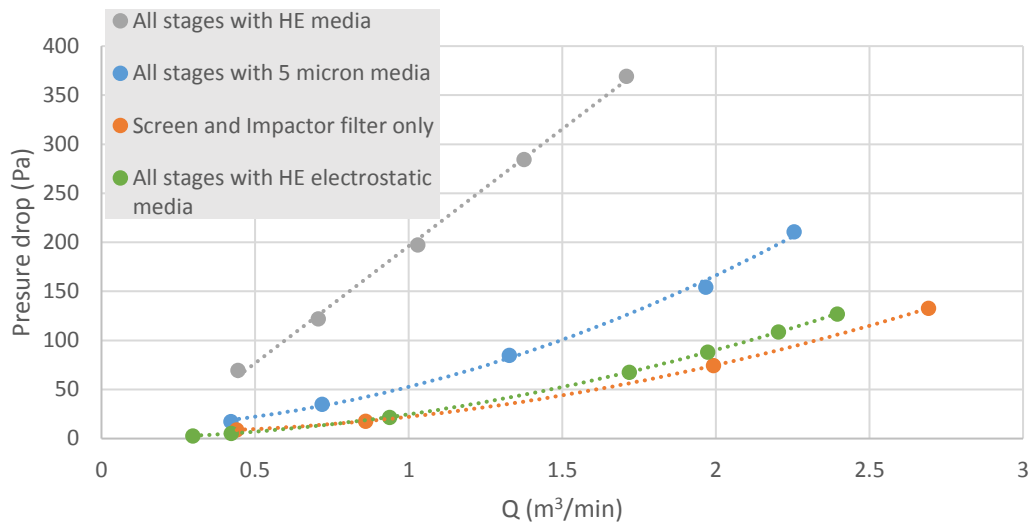
The flow performance curves for the different media, including the partial configuration (“screen and impactor filter only” or no media), are given in Fig. 4. As can be seen, the curves exhibit a clear rise in pressure drop with flow rate which are evidently quite distinct for each of the media cases and partial (no media) configuration. The pressure drop from the partial configuration was naturally the lowest but exhibited a non-linear trend. This is somewhat expected as the discharge coefficient through openings such as an orifice or the slits of the impactor can be flow or Reynolds number dependent, particularly for low Reynolds number as in this application.<sup>14</sup>

The pressure drop of the full SFS configuration (all stages) with the felt media, shown in Fig. 4, is higher than the partial configuration. The increased pressure drop is due to the contribution of the felt media in the SMF stage. This pressure drop contribution was comparable or even less than the pressure drop from partial configuration. The pressure drop also increased non-linearly, which was similar to the behavior of the partial configuration. The full SFS configuration with the HE electrostatic media produced the lowest pressure drop of all the media tested. It was just slightly above the pressure drop of the screen and impactor in the partial configuration, and generally followed the trend of the impactor. This is expected since the media only added a small contribution to the overall pressure drop, which was dominated by the pressure drop through the impactor. The pressure drop when the SFS was configured with the HE media was significantly higher than in the configurations with the felt media case and the HE electrostatic media. In fact, the pressure drop from the HE media at a flowrate of 1.7 m<sup>3</sup>/min was higher by about 7.5 times than the HE electrostatic media and more than three times higher than the corresponding pressure drop from the felt media. Although the increase in pressure drop was linear with flow rate, indicating nominal flow performance of the media, as will be shown, the corresponding media velocities were significantly above the operational range for nominal filtration performance. Also, the flow apparatus could not—without some reconfiguration of the apparatus duct arrangement—achieve the 1.98 m<sup>3</sup>/min ISS target flowrate because of the excessive pressure drop induced by the HE media.

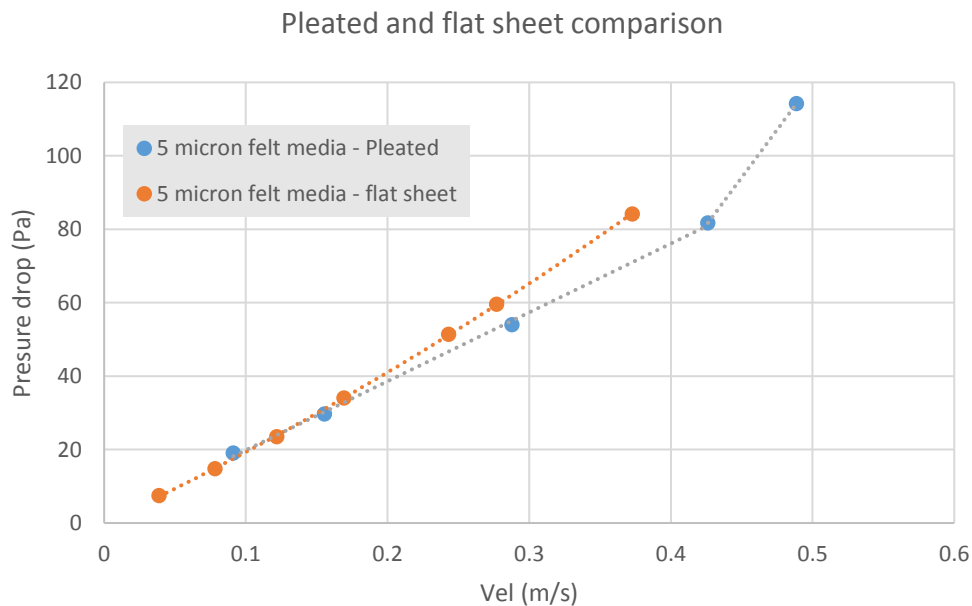
For reference, a comparison of the above pressure drop data of the pleated configuration to test results in a flat sheet configuration is provided in Figs. 5 and 6. The purpose of this comparison was to determine if there were any configuration losses due to the pleating and scrolling of the media. The flat sheet of media was inserted between duct section in the same location as the filter article in Fig. 3, and foam stripping was used to the seal the sheet to the duct flanges. The media velocity, which is the velocity component normal to the surface of the media in either the pleated or flat sheet configuration, was calculated from the incoming flow velocity and the total exposed surface area in both configurations. The total surface area of the pleated configuration was calculated from the area of the two faces of an individual pleat and the number of pleats. To calculate the pressure drop due to the media alone, the measured pressure drop values from the impactor and screen (partial configuration) were curve fitted as a function of flow rate, and its contribution was subtracted out from the total pressure drop (which included the media). In the felt media case, the pressure drop rises linearly with media velocity, in both the flat sheet and the pleated configurations, with the pleated configuration having a slightly smaller slope and slightly lower values at the larger face velocity. The rise in pressure drop takes on a non-linear trend at the 0.4 m/s mark. In the HE case, Fig. 6, the pressure drop curves are close in value at the lower end of the media velocity range, however, the slopes begin to spread and vary between the two configurations as the flowrate is increased. In addition, at the lower velocity range the two configurations appear to converge to the manufacturer’s specified performance point (44.8 Pa @ 5 cm/s media velocity). Lastly, this chart shows the dramatically smaller pressure drop and slope of the pressure drop of the HE electrostatic media. There was a slight difference in the pressure drop plot between the flat sheet and pleated configurations of this media. In the pleated configuration, the pressure drop appeared to have the same slope but was shifted down from that of the flat sheet configuration. It could be that a slight discrepancy in the flow rate reading, for example, could have shifted these plots. Since this pressure drop difference between the two configurations is relatively small, the two configurations are considered to provide similar flow performance.

It should be noted that the slope of the pressure drop, in general, is lower in the pleated configuration for all filter media cases. This points to possible leaks or pressure losses in the housing around the filter particularly at the edges

of the media where it was not fully sealed. A clear source of these pressure losses was linked to the gaps created around the edges of the media as the media is deployed over the guide tracks and rollers in the internal volume of the filter housing. This source of the leakage is exacerbated with the higher flow rates and less permeable (higher pressure drop) media because the media starts to bow out in the direction of the flow and opens up contacting or interface surfaces that are normally in tighter contact under low flow or no flow conditions. This effect leads to large pressure losses (i.e. losses in pressured drop) at large flow rates which explains the pronounced difference in performances seen in Fig. 6 for the HE media. In this case, the media inherently produces large pressure drops and therefore has a strong tendency to bow out and deform, leading to considerable losses and significantly reduced pressure drops as just described.

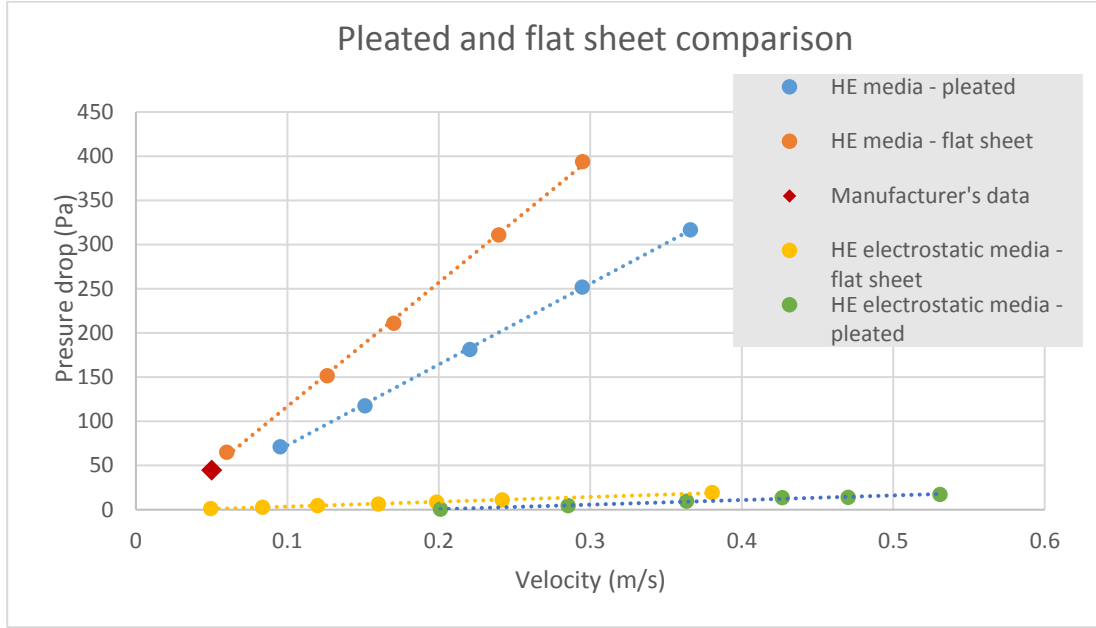


**Figure 4: Flow rate vs Pressure drop for the BFE Scroll Filter**



**Figure 5: Comparison of media velocity vs. pressure drop for felt media pleated and flat sheet configurations**





**Figure 6: Comparison of media velocity vs. pressure drop for HE and HE electrostatic media in pleated and flat sheet configurations**

### C. Collection efficiency and penetration tests

The results of the ISO Fine Dust Test (FDT) challenge are presented in the plots of Fig. 7. The two optical particle counter (OPC) used this test discriminate counts between different particle sizes. In this case, six different particle size bins or channels were measured: 0.3  $\mu\text{m}$ , 0.5  $\mu\text{m}$ , 1  $\mu\text{m}$ , 2.5  $\mu\text{m}$ , 5  $\mu\text{m}$ , and 10  $\mu\text{m}$ . The collection efficiency at each of the particle sizes is given by

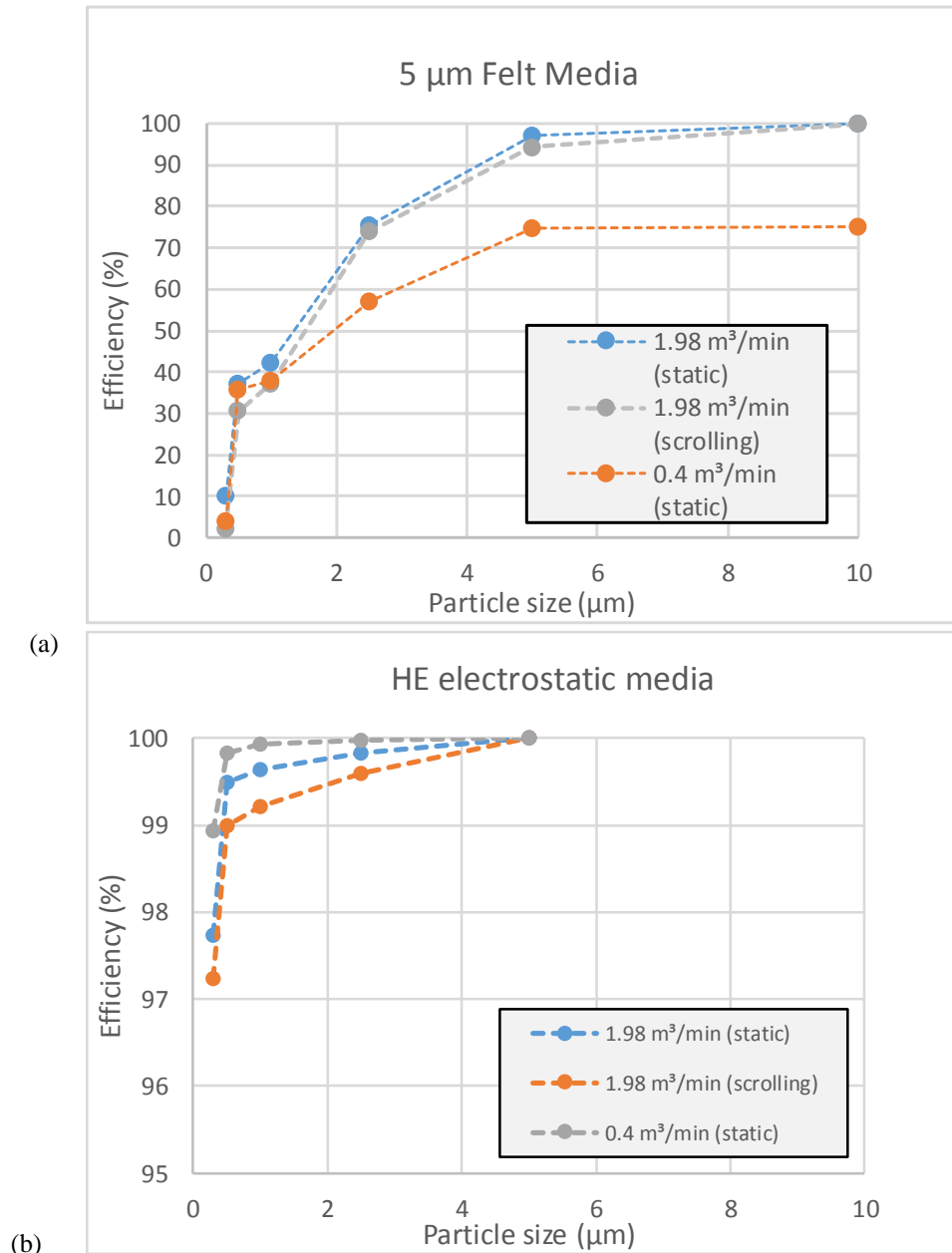
$$E = 1 - \frac{N_{\text{downstream}}}{N_{\text{upstream}}} \quad (2)$$

Where N represents the particle counts at the given location and for a specific particle size, that is provided by the OPCs.

In the felt media case, Fig. 7a, a roll-off in collection efficiency starting at the 5  $\mu\text{m}$  particle size was found. The diameter at which the collection efficiency reaches 50%,  $d_{50}$ , called the cut size, is typically used to define the particle cut-off size of particle collection devices. The flow rate through the media had an effect on the overall collection efficiency. In the felt media case, the  $d_{50}$  appears to be centered around 2  $\mu\text{m}$  at 0.4  $\text{m}^3/\text{min}$  and further reduces to around 1.2  $\mu\text{m}$  for 1.98  $\text{m}^3/\text{min}$  case. Almost 100% of particles 5  $\mu\text{m}$  and larger were captured on the media for all flow rates. The data also showed a slight to negligible drop in collection efficiency during the scrolling operation indicating that no additional leak paths were produced as a result of this operation. As seen in Fig. 7b, the HE electrostatic media provided dramatically better collection efficiencies at the small particle sizes. In fact, it shows that the media provided close to 100% capturing efficiency down to a particle size of 0.5  $\mu\text{m}$ . During the scrolling operation, the efficiency dropped by at most 1%, which is still considered small. The HE media's performance was not testable under the ISO FTD challenge since its MPPS size range was below the detection range of the optical counters, and rather its particle penetration was measured using the liquid aerosol penetration tests described next.

Liquid aerosol based penetration tests were performed on the HE and HE electrostatic media filter configurations. Table 3 presents the results of these tests. While the HE media is specified to provide around 60% efficiency, the test data showed that media significantly underperformed. There a couple of reasons for this. First, the media was being operated in a range significantly above its rated media velocity due to the limited number of pleats and smaller exposed surface area of the media in the SMF stage. It has been well established in the filtration literature that filter efficiency drops off quickly when it is operated at velocities significantly above its rated media velocity, and conversely noticeable increases in efficiency when operated at significantly lower flowrates.<sup>8</sup> Secondly, leaks around the media,

particularly around the edges, can alter the overall media efficiency. One test to check for leaks is to perform a penetration test at a much lower flow rate than the target flow rate. In this case, the efficiency should noticeably rise as the flow rate is reduced. The data shows that when the flow rate was dropped to about 20% of its target flow rate the value of efficiency improved only marginally. This indicates that there may have still been some small leaks around the media. The underperformance of the HE media in collection efficiency combined with the excessive pressure drop it produced is a significant drawback for its use in the Scroll Filter. The HE electrostatic media, also underperformed but this is somewhat expected since this media was not specifically designed to filter out Mil Standard MPPS particle sizes. Finally, a quick penetration test of a flat sheet of felt media immediately showed that there was 100% penetration through the media.



**Figure 7: Measured particle collection efficiencies for (a) 5 μm felt filter media, and (b) the HE electrostatic media.**

**Table 4: Aerosol Penetration Test Results**

Config.	Flow rate (m <sup>3</sup> /min)	Penetration (%)	Efficiency (%)
Scroll (HE media)	0.4	55.89	44.11
Scroll (HE media)	1.98	57.11	42.89
Scroll (HE electrostatic media)	0.4	59.00	41.00
Scroll (HE electrostatic media)	1.98	70.00	30.00

#### D. Analysis

Legacy filter systems, such as the BFE's on the ISS, give some guidance on the range of pressure drops permissible in the life support system architecture. System architecture requirements typically impose a minimum on pressure drop, and in the case of the ISS US modules the pressure drop is kept below 124.5 Pa at a flow rate of 1.98 m<sup>3</sup>/min per filtration unit. However, systems that produce upwards of this pressure drop value but that provide other added benefit are worth consideration. From this perspective, the present results show a clear demarcation in performance between the different filter media types.

The overall pressure drop through the fully staged BFE-SFS with the felt media was about 149 Pa at the 1.98 m<sup>3</sup>/min target flow rate, with the screen and impactor filter and the felt media each contributing about half of this pressure drop. This contrasts with the 374 Pa for the HE media at a flowrate of 1.7 m<sup>3</sup>/min with the media itself producing 324 Pa, or greater than 86 % of the pressure drop of the filter system. The flow apparatus even failed to achieve the target flow rate of 1.98 m<sup>3</sup>/min in our setup due to the excessive pressure drop from the HE media. The HE electrostatic media produced the smallest pressure drop among all the media, with a pressure drop of 88 Pa at 1.98 m<sup>3</sup>/min. From visual inspection, the media's low pressure drop stems from its expanded microstructure which is quite open (i.e. can easily let light in). Despite the very open structure, the media was shown to have high collection efficiency.

The main reason that the pressure drops are generally higher in the SFS than in the legacy SOA filters, particularly in the HE media case, is due to the design of the Scroll filter. First, unlike commercially available pleated filter elements with high pleat density, the limited number of pleats in the Scroll filter also limits the total exposed surface area of the media in this prototype. It should be emphasized that the advantage of the pleats in the Scroll media stage is that it increases surface area over that of a simple flat sheet, while allowing the pleated media to be renewed with new or fresh media. The larger surface area provided by the pleats in turn increases filtration capacity and reduces pressure drop. The increase in surface area also allows the use of better than pre-filter media because of the reduced media velocity. One way to reduce the pressure drop in the Scroll filter is by increasing the number of pleats, however the challenge is that this adds more complexity in the highly constraint hardware volume.

While the felt media performed well, no manufacturer's pressure drop data in air was available for comparison, unlike the case of the HE media. To achieve an estimate, or order of magnitude, of the pressure drop Darcy's law (Eq. 1) which relates the pressure drop to the medium's permeability, fluid viscosity and flow rate is invoked:

$$\Delta p = \mu / \kappa Q \quad (1)$$

Available operational data (from various online sources) for the felt media indicates a rating of 120 gpm (gallons per minute) in water and pressure drops usually measured in pounds per square inch (psi). Since the ratio of viscosities between water and air is about 100 fold, this translates into a pressure drop ranging in the inches of water for comparable flow rates (flat sheet comparison). Thus, the pressure drop in the range of 25 to 124 Pa, as presented in Fig. 4, for the felt media is consistent with these estimated values.

Due to the design and operation of the SFS, it was challenging to maintain near leak-free conditions around the media. In fact, some level of leakage is unavoidable in order to allow for media scrolling. Consequently, it would be prohibitive to use HEPA grade media in the SFS because of the high pressure drop it produces, and therefore a lower grade media, even up to sub-HEPA class media, would be more appropriate for the SFS. In the SMF stage, the edges of the media slide inside guide tracks. By design, the close fit between the media thickness and track width, as well as the hydrodynamic load on the media pressing against the inside surface of the track on the low-pressure side, was expected to provide a nearly complete seal of the media edges. However, a good seal is very difficult to achieve around the edges of the media that needs to be translated across the guide tracks during the scrolling operation, particularly with less permeable media producing high pressure drops. The leaks around the edges of the media lead to a lowering of the pressure drop at the cost of lower particle collection efficiency, because of particles passing through the leak paths. As a result, the media's resistance (pressure drop) as well as the collection efficiency is impacted by the leakage at the media edges. In light of this limiting issue, the HE media will not likely be a consideration for the Scroll BFE unless the pressure drop can be significantly reduced. One obvious way is by increasing the number of pleats by 50% or more, but as mentioned earlier this translates into more complexity to the system. In contrast, the felt media, with its inherent lower pressure drop, was considerably less impacted by edge leakage as can be seen in Fig. 5 where a close match in pressure drop was found between the pleated configuration and the flat sheet configuration in which the media edges were completely sealed. However in general, a method of better sealing the edges of the media will significantly improve the performance of the filter system with any grade of media.

The results of the ISO FTD dust challenge tests showed good filtration performance for the 5  $\mu\text{m}$  rated felt media. It achieved a  $d_{50}$  cut size of less than 2  $\mu\text{m}$  and virtually 100% particle capture for particles 5  $\mu\text{m}$  and larger at 1.98  $\text{m}^3/\text{min}$ . This is a significant result since this ensures that a substantial amount of the airborne PM down to 2  $\mu\text{m}$  is removed from the cabin air in a spacecraft application. If a high efficiency finishing filter (e.g. HEPA filter) is additionally used, the Scroll BFE will significantly reduce the particle mass load on the finishing filter and significantly extend its operational life. This combined with the low pressure drop offers features that trade well for the Scroll BFE. The HE electrostatic media provided significantly better filtration performance. In fact, the HE electrostatic filter seemed to trade the best, both because of the high collection efficiency performance and substantially low pressure drop. In addition, its lightweight material density and thin media dimension makes it attractive from a launch payload perspective and also facilitates integration into the housing of the SFS.

## VII. Conclusion

The results of the present tests on the SFS showed a clear demarcation in performance of the various media. The data showed that the pressure drop obtained with felt media and HE electrostatic media was in a suitable range of operation, while the pressure drop of the HE media was quite excessive in comparison to the nominal pressure drop of legacy filters on the ISS. The Scroll BFE filter with the felt media can provide a substantial benefit as a pre-filter. First, it will provide the primary benefits of the SFS, i.e. tailored media filter performance, regeneration, and compact and safe storage of the PM debris in the used rolls of media. In addition, it will substantially reduce the PM load above the 2  $\mu\text{m}$  particle size in the return air to the cabin and reduce the load on the finishing filter. The drawback to the felt media is its greater thickness compared to high efficiency media which will limit the amount of clean media that can be packed into the filter system for any deep space mission. The HE electrostatic media provided the best performance among all the media tested, with high collection efficiency down to the submicron range, and is clearly worth considering in future developments and testing of the SFS. Future work will involve continuing to evaluate other media that could provide greater filtration efficiency while providing low pressure drop. In addition, components that enhance the scrolling and regeneration performance, and design and structural options that help achieve optimum mass savings to reduce launch cost will be sought to further enhance performance and help meet future mission requirements. The benefits in mass savings as suggested in the Mars trade study, and in the use of lighter materials and components, and reduced maintenance, is expected to outweigh the additional power requirement and complexity of the system. Lastly, long duration testing under simulated environmental test conditions and operational parameters will eventually be required to advance the readiness level of the filter system.

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report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

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